



# Azimuthal Jet Tomography at RHIC and LHC

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## Abstract

A generic jet-energy loss model that is coupled to state-of-the-art hydrodynamic fields and interpolates between a wide class of running coupling pQCD-based and AdS/CFT-inspired models is compared to recent data on the azimuthal and transverse momentum dependence of high- $p_T$  pion nuclear modification factors and high- $p_T$  elliptic flow measured at RHIC and LHC. We find that RHIC data are surprisingly consistent with various scenarios considered. However, extrapolations to LHC energies favor running coupling pQCD-based models of jet-energy loss. While conformal holographic models are shown to be inconsistent with data, recent non-conformal generalizations of AdS holography may provide an alternative description.

**Keywords:** heavy-ion collisions, quantum chromodynamics, AdS/CFT, jet-energy loss, hydrodynamics

## 1. Introduction

Tomographic information about the evolution of the quark-gluon plasma (QGP) formed in a high-energy nuclear collision is commonly extracted by jet-quenching observables which, however, depend on the details of both the jet-medium dynamics,  $dE/dx(E, \vec{x}, T)$ , as well as the bulk temperature and flow velocity fields. Recently, PHENIX [1] compared their measured data on the nuclear modification factor in- and out-of-plane to different perturbative QCD (pQCD)-based and one AdS-CFT motivated jet-energy loss model, considering a longitudinal and transverse expanding hydrodynamic background. Their result strongly suggest that only the AdS-inspired model explains *both* the nuclear modification factor and the high- $p_T$  elliptic flow accessible through  $R_{AA}^{\text{in/out}} = R_{AA} (1 \pm 2v_2)$ . While the yield of nuclear modification factor could as well be described by the pQCD-based AMY, HT, and ASW models considered, their high- $p_T$  elliptic flow is significantly too low. This is in line with the results in Ref. [2] and [3], showing that the pQCD (D)GLV energy loss prescription coupled to either the 3D MPC parton transport model [4] or the (2+1)D transverse expansion of VISH2+1 [5] applying a temperature-independent running coupling lead to a high- $p_T$  elliptic flow that is by a factor of  $\sim 2$  smaller than the measured data, while the  $R_{AA}$  can well be reproduced. The aim of the present work is to braden the PHENIX analysis by considering a wider class of  $dE/dx$  models coupled to different flow fields and by extending the analysis to a simultaneous description of RHIC and LHC. We study models based on pQCD, conformal and non-conformal AdS holography, as well as a phenomenological prescription with an enhanced jet-energy loss around the transition temperature of  $T_c \approx 170$  MeV (referred to as SLTc [6]). Each model is coupled to different bulk QGP collective fields as given by (1) VISH2+1 [5], (2) the RL (Romatschke-Luzum) Hydro [7], and (3) a simple  $v_\perp = 0.6$  transverse blast wave model [8].

The generic energy-loss model considered [9, 10] is characterized by the jet energy, path length, and thermal-field dependence described via the three exponents ( $a, b, c$ ):

$$\frac{dE}{dx} = \frac{dP}{d\tau}(\vec{x}_0, \phi, \tau) = -C_r \kappa(T) P^a(\tau) \tau^b T^c. \quad (1)$$

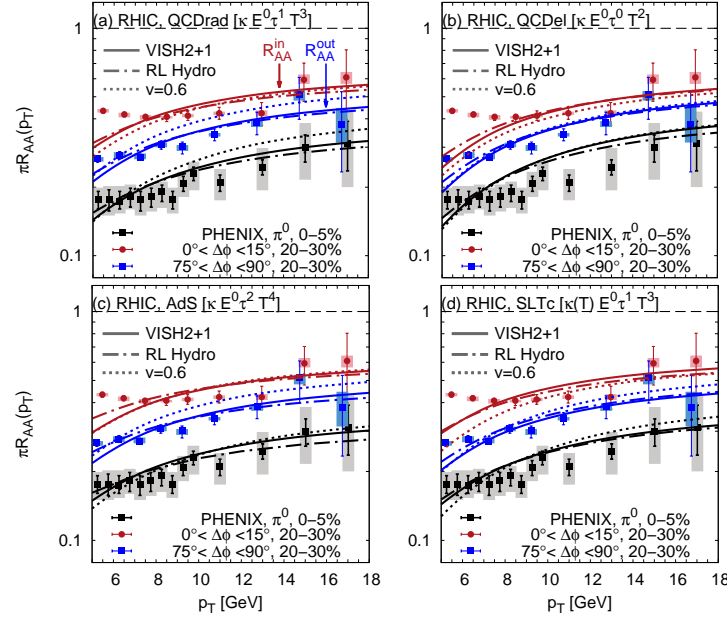


Figure 1. In- and out-of-plane nuclear modification factors for 0-5% and 20-30% centrality at RHIC [1], compared to predictions simulating (a) a running coupling QCD energy loss, (b) an elastic jet-energy loss, (c) a conformal AdS falling string scenario, and (d) the transition-phase dominated SLTc model. For each model, three different bulk evolutions are studied: ideal VISH2+1 [5] (solid), viscous  $\eta/s = 0.08$  RL Hydro [7] (dashed-dotted), and the  $v_{\perp} = 0.6$  blast wave model [8] (dotted).

Here,  $T = T[\vec{x}(\tau) = \vec{x}_0 + (\tau - \tau_0)\hat{n}(\phi)]$  is the local temperature along the jet path at time  $\tau$  for a jet produced initially at time  $\tau_0$  and distributed according to a Glauber transverse initial profile [10]. For dimensionless couplings,  $c = 2 + z - a$ .  $\kappa(T)$  can depend on the local temperature field (SLTc model).  $C_r = 1(\frac{2}{3})$  describes quark (gluon) jets.

In the following, we particularly distinguish four different cases: (1) a running coupling QCD energy loss QCDrad ( $a = 0, b = 1, c = 3$ ), (2) an elastic jet-energy loss [9] QCDel ( $a = 0, b = 0, c = 2$ ), (3) a scenario characterized by a conformal falling string [11] AdS ( $a = 0, b = 2, c = 4$ ), and (4) a  $T_c$ -dominated energy loss [6] with  $\kappa(T_c) = 3\kappa(\infty)$  SLTc ( $a = 0, b = 1, c = 3$ ). For each scenario, the jet-medium coupling is adjusted to fit a single reference point at  $p_T = 7.5$  GeV for RHIC energies.

## 2. Discussion and Results

The most striking result in Fig. 1 is that in contrast to the PHENIX results [1] *all* scenarios based on a (viscous) hydrodynamic background describe the measured  $p_T > 8$  GeV data within the present error bars. Only the  $v_{\perp} = 0.6$  transverse blast wave background leads to an in/out asymmetry with a factor of two below recent PHENIX data. The qualitative difference to the PHENIX results, in particular to the different slope of the  $R_{AA}^{\text{in/out}}$ , is due to various details of the hydrodynamic simulation and the jet-energy loss prescription. In the study shown by PHENIX, the flow field was computed with an ideal (non-dissipative) hydrodynamic code assuming a Bag model first-order phase transition while the VISH2+1 code considered here is based on a smoothed (SM-EoS Q) equation of state (EoS) and the viscous RL Hydro employs a more realistic continuous crossover transition.

Given this difficulty of untangling the background and jet-energy loss effects at one particular  $\sqrt{s}$ , we continue by exploring the dependence of the jet asymmetry on the collision energy and study LHC conditions, see Fig. 2, for the four jet-energy loss scenarios and the three background fields introduced above. However, in contrast to RHIC data, at LHC energies the nuclear modification factors and the high- $p_T$  elliptic flow are only issued separately (i.e. not as  $R_{AA}^{\text{in/out}}$ ). Therefore, we have to split up the LHC results into two subplots for each scenario (see Fig. 2).

For the pQCD-based scenarios QCDrad and QCDel, we assume a running coupling effect [9]. I.e. the jet-medium coupling  $\kappa_{LHC}$  is reduced by  $\sim (30-40)\%$  as compared to  $\kappa_{RHIC}$ . As shown in Fig. 2(a1) and (a2), QCDrad reproduces

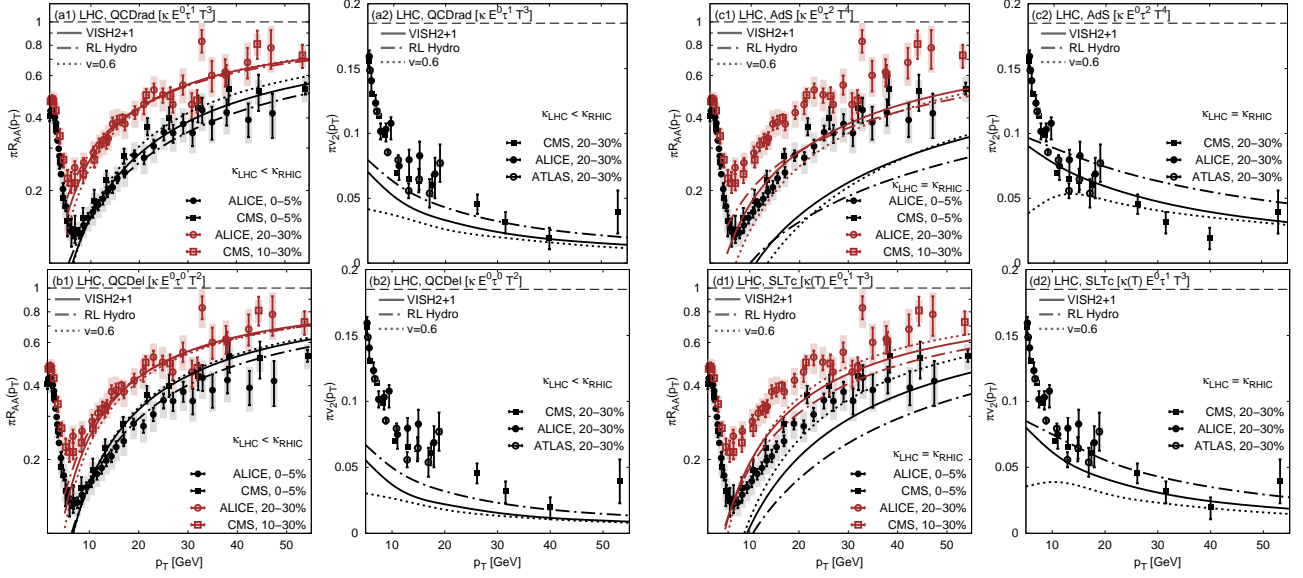


Figure 2. The nuclear modification factors and high- $p_T$  elliptic flow for most central and mid-peripheral centralities at LHC energies. The nuclear modification factor is taken from ALICE [12] and CMS [13], the high- $p_T$  elliptic flow is extracted from ALICE [14], CMS [15], and ATLAS [16]. The model calculations are the same as in Fig. 1. However, the bulk QGP fields are taken from viscous ( $\eta/s = 0.08$ ) VISH2+1 [5] (solid), viscous  $\eta/s = 0.08$  RL Hydro [7] (dashed-dotted), and the  $v_\perp = 0.6$  blast wave model [8] (dotted). For panels (a) and (b), the jet-medium coupling  $\kappa_{LHC}$  is reduced relative to RHIC to simulate a QCD running coupling, while  $\kappa_{LHC} = \kappa_{RHIC}$  is considered in panels (c) and (d), see text.

both the nuclear modification factors and the high- $p_T$  elliptic flow within the uncertainties of the bulk space-time evolution given, amongst others, by the initial condition, the shear viscosity over entropy ratio ( $\eta/s$ ), and the initial time  $\tau_0$ . This running coupling QCD energy loss, however, appears to be preferred over the elastic jet-energy loss QCDel [Fig. 2(b1) and (b2)] .

In contrast to those pQCD cases discussed in Fig. 2(a) and (b), we do *not* consider a QCD running coupling effect for the AdS-inspired energy loss and the SLTc model shown in Fig. 2(c) and (d) but assume that  $\kappa_{LHC} = \kappa_{RHIC}$ . In the AdS case, the reason is that *conformal* AdS/CFT implies scale invariance and thus does not allow for a running but only a fixed coupling. As can be seen from Fig. 2(c1), this fixing of the jet-medium coupling at RHIC energies leads to the well-known overquenching of the nuclear modification factor [9] and thus to an enhancement of the high- $p_T$  elliptic flow as compared to the pQCD scenarios.

This Fig. 2(c1) proves that *conformal* AdS/CFT is ruled out by the yield and the rapid rise of the  $R_{AA}(p_T)$  at LHC energies.

Since the SLTc model shown in Fig. 2(d1) and (d2) is a pQCD-based model as well, a running coupling effect might apply. However, we choose the same jet-medium coupling as for RHIC energies since it was shown in Ref. [6] that the SLTc model can describe the nuclear modification factor and the high- $p_T$  elliptic flow both at RHIC and at LHC without any additional running coupling effect for a purely longitudinally expanding medium. Thus, Fig. 2(d1) and (d2) proves that for a more realistic (2+1)D expanding medium the temperature dependence of the jet-medium coupling around a critical temperature of  $T_c = 170$  MeV is not sufficient to describe the nuclear modification factor at LHC energies.

While we showed in Fig. 2(c1) and (c2) that *conformal* AdS/CFT is ruled out by the data, a recent non-standard AdS/CFT formulation of “shooting” strings [17] leads to an analytic jet-energy loss formula that interpolates between the above discussed extremes of QCDel and AdS (because the path-length dependence within this prescription is itself temperature dependent). This ansatz suggests that it might be necessary to broaden the scope of the AdS/CFT models to *non-conformal* scenarios. For a non-conformal AdS/CFT description, the coupling constant can run. Allowing a running coupling effect for an AdS/CFT-inspired energy loss of  $dE/dx \sim E^0 \tau^2 T^4$  results in nuclear modification factors and high- $p_T$  elliptic flow at LHC energies that are consistent with the measured data within the current experimental error bars as shown in Fig. 3.

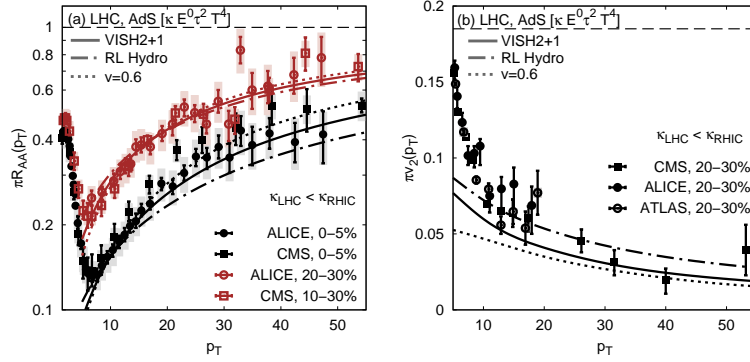


Figure 3. The nuclear modification factors and high- $p_T$  elliptic flow for most central and mid-peripheral centralities at LHC energies, cf. Fig. 2, compared to a non-conformal AdS-inspired energy-loss scenario with  $dE/dx = \kappa E^0 \tau^2 T^4$ , allowing for a running coupling  $\kappa_{LHC} < \kappa_{RHIC}$ .

### 3. Summary

We compare recent data on the nuclear modification factors measured at RHIC [1] and LHC [12–16] to a wide class of jet-energy loss models [10] based on perturbative QCD (pQCD), conformal and non-conformal AdS holography, and a phenomenological model with an enhanced energy loss around the transition temperature of  $T_c \approx 170$  MeV, coupled to different recent bulk QGP collective fields [5, 7, 8]. We found that (1) a running coupling pQCD energy loss seems to be favored, (2) a realistic QGP flow backgrounds is essential to simultaneously describe *both* the nuclear modification factors and the high- $p_T$  elliptic flow, and (3) *conformal* AdS string-like jet holography appears to be ruled out by the LHC data while novel non-conformal generalizations of string models [17] may provide an alternative description. Further details of the present study, especially a discussion on the differences between the energy-loss model studied here and other pQCD energy-loss prescriptions will be presented elsewhere [18].

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